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1 **Real-World CO₂ and NO_x Emissions from Refrigerated Vans**

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5 **Abstract:**

6 Refrigerated vans used for home deliveries are attracting attention as online
7 grocery shopping in the UK is expanding rapidly and contributes to the increasing
8 greenhouse gas (CO₂) and nitrogen oxides (NO_x) emissions. These vans are
9 typically 3.5-tonne gross weight vehicles equipped with temperature-controlled
10 units called Transport Refrigeration Units (TRUs), which are usually powered off
11 the vehicles' engine. It is obvious that vehicles with added weight of TRUs
12 consume more fuel and emit more NO_x, let alone the vehicles' diesel engines are
13 also powering the refrigeration units, which further elevates the emissions.

14 This research uses an instantaneous vehicle emission model PHEM (version
15 13.0.3.21) to simulate the real-world emissions from refrigerated vans. A
16 validation of PHEM is included using data from laboratory (chassis dynamometer)
17 tests over a realistic driving profile (the London Drive Cycle), to assess its ability
18 to quantify the impact of changing vehicle weights and carrying loads. The impact
19 of the TRU weight, greater frontal area increasing aerodynamic drag and

20 refrigeration load on van emissions is then estimated by PHEM. The influence of
21 ambient temperature, cargo weight and driving condition on CO₂ and NO_x
22 emission from refrigerated van are also assessed.

23 Overall CO₂ emissions of vans with TRUs are found to be 15% higher than
24 standard vehicles, with NO_x emissions estimated to be elevated by 18%. This
25 confirms the need to take into account the impact of additional engine load when
26 predicting van emissions in this and other sectors such as ambulances which are
27 relatively heavy, high powered vehicles. Moreover, findings of the impact of TRUs
28 on fuel consumptions can be used to optimize fuel-saving strategies for
29 refrigerated vans and test cases for alternative low- or zero-emission
30 technologies, to support progress to a sustainable net-zero society.

31 **Keywords:**

32 real-world emissions, light commercial vehicles, transportation refrigeration units
33 (TRUs), PHEM, Carbon Dioxide (CO₂), Nitrogen Oxides (NO_x)

34 **1. Introduction**

35 Estimation of road transport emissions in the UK shows that light commercial
36 vehicles (LCVs), or vans have seen the fastest growth in both CO₂ and NO_x
37 emissions, accounting for 17% of CO₂ emissions and 35% of NO_x emissions in
38 2017 ([NAEI, 2019](#)), while van numbers only make up around 10% of total licensed
39 vehicles ([DfT, 2018b](#)). One of the main factors contributing to the increasing van
40 emissions is the rapid rise in the heavy class III¹ van demand ([SMMT, 2019](#)).
41 Heavy vans are deployed for a wide range of services such as construction,
42 refrigerated food delivery and ambulances. These vans are always with additional
43 engine load, which is more polluting than standard, un-modified vehicles. Among
44 all the modified vans with high-power demands, refrigerated vans are considered
45 the most important due to their growing fleet share as online grocery continues
46 to gain market over the recent years ([Braithwaite, 2017](#)).

47 Refrigerated vans are typically 3.5-tonne gross weight vehicle equipped with
48 temperature-controlled units called Transport Refrigeration Units (TRUs), which
49 are usually powered off the vehicles' diesel engine. It is obvious that vehicles with
50 added weight of TRUs consume more fuel and emit more NO_x, let alone the
51 vehicles' diesel engines are also powering the refrigeration units, which further
52 elevate the emissions. [Braithwaite \(2017\)](#) suggested that there were 15,000
53 refrigerated vans used for grocery home delivery in the UK in 2016 and the annual
54 distance travelled by refrigerated vans is at least twice the average ([DfT, 2019](#)).
55 The COVID-19 outbreak has also accelerated online grocery shopping and home

¹ Vans in the UK are defined as 4-wheel vehicles constructed for transporting goods and having a gross weight of 3500kg or less. They can be further classified into three sub-categories by reference mass, where class I are vans less than 1305kg, class II are those between 1305kg and 1760kg, and class III are those above 1760kg.

56 delivery orders were found to grow by 38% from 2.1 million to 2.9 million per
57 week² in the UK.

58 Despite the fact that vans have contributed a significant proportion to total UK's
59 CO₂ and NO_x emissions, the majority of existing studies focus on the passenger
60 car emissions ([Carslaw, D.C. et al., 2013](#); [Chen and Borcken-Kleefeld, 2016](#);
61 [Pavlovic et al., 2016](#)). Considering many studies have already demonstrated the
62 gap between laboratory and real-driving emissions for passenger cars ([Carslaw,
63 D. et al., 2011](#); [O'Driscoll et al., 2018](#); [Tietge et al., 2019](#)), it is expected there is
64 a significant divergence for vans as well. Besides, all the European emission
65 standard for vans follow passenger cars³ by one year. Time delays between
66 emission legislation and its effective implementation may well lead to a larger
67 discrepancy between van emissions generated from lab test cycle and real-world
68 driving. In order to better understand and control the negative impact of CO₂ and
69 NO_x emissions on public health and the environment, it is considered both timely
70 and significant to examine on-road emissions from vans.

71 To assess the environmental impact of vehicle exhaust pollutants, numerous
72 emission models have been developed. Macroscopic emission models based on
73 average speed or traffic situations (e.g. MOBILE, COPERT, HBEFA, ARTEMIS)
74 ([Smit et al., 2008](#)) are suitable for emission estimation for national or regional
75 inventories, but they might be unreliable when applied to local traffic situations

² <https://www.gov.uk/government/speeches/environment-secretarys-statement-on-coronavirus-covid-19-26-april-2020>

³ The latest Euro 6d temp and Euro 6d requires light-duty vehicles to meet corresponding 'not to exceed' limits in Real Driving Emissions testing (RDE) procedure before they could be placed on the market. The RDE test has gradually taken effect since 2017 and will apply to all new passenger cars by the beginning of 2021 and all new vans by the beginning of 2022 (Commission Regulation (EU) 2017/1151).

76 ([Ahn and Rakha, 2008](#)). Microscopic emission models (e.g. PHEM, MOVES)
77 ([Boulter et al., 2007](#)) better capture vehicle emission behaviour given that they
78 require detailed input data such as second-by-second speed profile, altitude and
79 signals, as well as the design and operation strategy of engine and powertrain
80 ([Küng et al., 2019](#)). Microscopic models are typically used in specific user test
81 cases and scenario testing, such as estimating the vehicle emissions of heavy
82 goods vehicles (HGVs) in port areas ([Zamboni et al., 2013](#)), optimizing transit
83 buses' cruising speeds range for fuel economy ([Wang and Rakha, 2016](#)), or
84 assessing the impact of the additional engine loads of road grade on fuel
85 consumption and exhaust emission ([Wyatt, 2017](#)). This paper uses PHEM
86 (Passenger Car and Heavy Duty Emission Model) to estimate the emissions from
87 refrigerated vans as it has one of the largest vehicle emission database ([Zamboni
88 et al., 2013](#)) compared to other instantaneous emission models, and it is capable
89 of accounting for the impact of increased weight, frontal area and refrigeration
90 load on its emissions.

91 The main focus of this paper is CO₂ and NO_x emissions from refrigerated vans
92 as CO₂ is directly linked to global warming and NO_x is detrimental to public health
93 and the environment. Independent chassis dynamometer tests over a realistic
94 on-road driving profile (the London Drive Cycle ([Moody and Tate, 2017](#))) are used
95 to validate PHEM's ability to simulate transient tail-pipe emissions and quantify
96 the impact of changing vehicle weights and carrying loads. The emission
97 performance of vans with additional loading of TRUs is then assessed by PHEM.
98 The influence of ambient temperature, cargo weight and driving condition on CO₂
99 and NO_x emission from refrigerated van are also evaluated.

100 **2. Method**

101 **2.1 PHEM characteristics and application to vans**

102 PHEM is an instantaneous vehicle emission model able to simulate second-by-
103 second fuel consumption and most relevant tail-pipe pollutant emissions based
104 on transient engine maps ([Hausberger and Rexeis, 2017](#)). PHEM was first
105 developed by the Institute for Internal Combustion Engines and Thermodynamics
106 at the Graz University of Technology (TUG, AU) in late 90's and has been
107 continually updated to include new technologies and advance the accuracy of
108 prediction.

109 As input, PHEM requires a defined driving cycle (speed curve and road
110 longitudinal gradient over time) at 1 Hz so it can calculate engine power demand
111 from the driving resistance and losses. It requires vehicle specifications (tyre
112 diameter, final drive and transmission ratio as well as a driver gear shift model)
113 to simulate engine speed, with default parameters available. The engine power
114 and engine speed are linked to an engine emission map specific to the test
115 vehicle type, which underpins the simulation of vehicle fuel consumption and
116 exhaust emissions (g/sec).

117 To represent average European vehicles, PHEM provide a set of predefined
118 "default vehicles", which is based on chassis dynamometer measurements from
119 HBEFA version 4.1 database. The database covers the most common vehicle
120 categories (passenger cars, vans, heavy duty vehicles) from Euro 0 to Euro 6
121 (including Euro 6a/b, Euro 6c, Euro 6d-Temp and Euro 6d) with gasoline-, diesel-
122 and alternatively-fuelled engine. For vehicles with selective catalytic reduction
123 (SCR) systems such as diesel Euro 6 vans, PHEM would also activate the
124 exhaust gas after-treatment model to achieve a more accurate prediction of NO_x

125 emissions. In the next section, average emission data in PHEM are compared
126 with test results of single vehicles to validate PHEM's capability to simulate
127 second-by-second fuel consumption (CO₂) and tail-pipe emissions in defined
128 driving cycles.

129 **2.2 Laboratory validation**

130 **2.2.1 Driving conditions and test vehicles**

131 Chassis dynamometer tests were conducted by Millbrook Proving Ground Ltd⁴
132 on behalf of Transport for London (TfL) over a drive cycle called the London Drive
133 Cycle (LDC). The tests were performed with a warm start, compliant with the
134 requirements of current type approval regulations⁵. During the tests the exhaust
135 pollutant was diluted continuously with ambient air using the Constant Volume
136 Sampling (CVS) system ([Costagliola et al., 2018](#)) and the emissions were
137 measured second-by-second using a gas analyser.

138 The LDC contains 9 sub-cycles, representing 3 different road types (urban,
139 suburban and motorway) under 3 different traffic conditions (AM peak, inter peak
140 and free-flow) ([Moody and Tate, 2017](#)). The speed profile of the LDC is illustrated
141 in Figure 1. The drive-cycle doesn't consider fluctuations in road gradient.
142 Measurement data from Millbrook Vehicle Emission Laboratory tested over the
143 LDC is considered to be authentic and representative of real-world driving
144 behaviour and vehicle emissions.

⁴ <https://www.millbrook.co.uk/services/vehicle-emissions-testing-facility-powertrain/>

⁵ The Millbrook Vehicle Emission Laboratory is in accordance with the requirements of Directive 2007/46 EC Article 41, Section 3 and has been designated as a Category A Technical Service for Individual Vehicle Approvals (IVA)

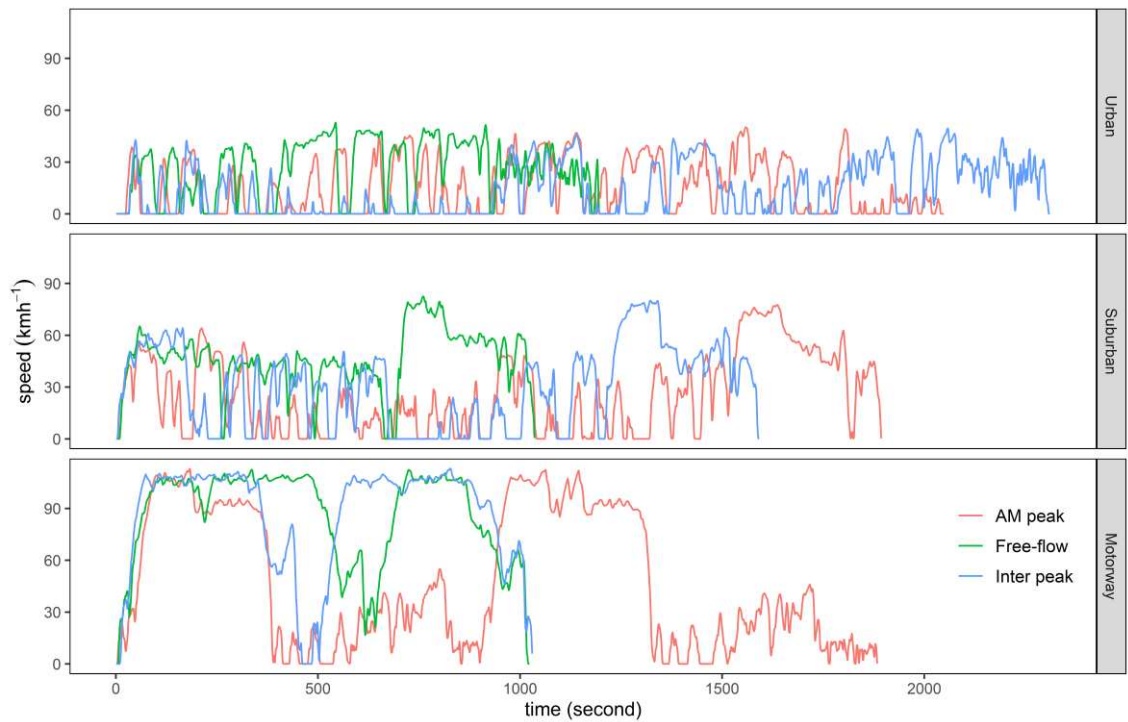


Figure 1 The London Drive Cycle speed profile

145 Two vehicles with different NO_x after-treatment systems were tested on chassis
 146 dynamometer over the LDC in this study. Vehicle A was a Euro 5 class III diesel
 147 LCV tested over the entire 140 km of the LDC, to verify PHEM's capability to
 148 simulate a standard van's fuel consumption and tail-pipe emission performance.
 149 Vehicle B was a Euro 6 small HGV tested over the suburban sub-cycle (free-flow
 150 and AM peak) in both un-laden (B1) and full-laden (B2) conditions. This allows
 151 PHEM's performance in quantifying the impact of changing vehicle weights and
 152 carrying loads to be evaluated. As vehicle B was a small HGV of 3450kg vehicle
 153 mass, we assume it had similar behaviours like a heavy van and is suitable for
 154 van validation. Detailed vehicle characteristics and drive cycle statistics are
 155 presented in Table 1.

Table 1 Technical specification drive cycle characteristics of each tested vehicles

Vehicle	A	B1	B2
Vehicle Category	N1 class III LCV	N2 HGV	N2 HGV
Vehicle Class	Euro 5 diesel	Euro 6 diesel	Euro 6 diesel
Engine Power (kw)	90	120	120
Vehicle Mass (kg)	2150	3450	3450
Vehicle Loading (kg)	375	0	4050
NOx after-treatment system	Exhaust gas recirculation (EGR)	Selective catalytic reduction (SCR)	Selective catalytic reduction (SCR)
Road Type	Urban, Suburban, Motorway	Suburban	Suburban
Time Period	Free-flow, AM Peak, Inter Peak	Free-flow, AM Peak	Free-flow, AM Peak
Duration (s)	14019	2930	2930
Distance (km)	140	27	27
Average Speed (km/h)	35.92	32.65	32.65
Maximum Acceleration (m/s ²)	2.67	2.67	2.67

156 Vehicle specifications such as rated engine power, vehicle mass and vehicle
157 loading were adjusted in PHEM's average vehicle folder to match the tested
158 vehicles in Table 1, where vehicle A belongs to LCV N1-III and vehicle B belongs
159 to HGV rigid truck (7.5-12ton). The LDC speed profile were also fed into PHEM

160 to match scenarios tested in the laboratory. When comparing laboratory
161 measurement and simulation results, the time shifts and instrument sensitivity
162 need to be considered. In chassis dynamometer tests, tail-pipe emissions have
163 been delayed and engine-out peaks smoothed through the exhaust analyser
164 systems (CVS), while PHEM aims to predict the instantaneous tail-pipe
165 emissions. In order to make laboratory measurements comparable with
166 instantaneous simulation results, emission data from PHEM has been processed
167 using a simple (equally weighted) moving-average method. By creating a series
168 of averages over 2 seconds, a moving-average method is able to smooth out
169 fluctuation in PHEM emission data and better track trend determination ([Hansun,
170 2013](#)). The time consistency between observed and modelled values has also
171 been checked before validation.

172 **2.2.2 Standard van validation**

173 Figure 2 presents PHEM's capability to predict vehicle A's tailpipe emissions from
174 three illustrative sample 300 second periods of the speed profile chosen to be
175 contrasting the LDC, which include driving in: an urban setting during the AM
176 peak (low speed, stop-start), a suburban district during inter peak (moderate
177 speed) and a free-flow, higher speed motorway driving conditions. The observed
178 and modelled CO₂ values (second panel) are in close agreement in all driving
179 conditions, while the observed NO_x values (bottom panel) for the specific test
180 vehicle are slightly higher than the modelled value in high speed driving
181 (Motorway, Free-flow section).

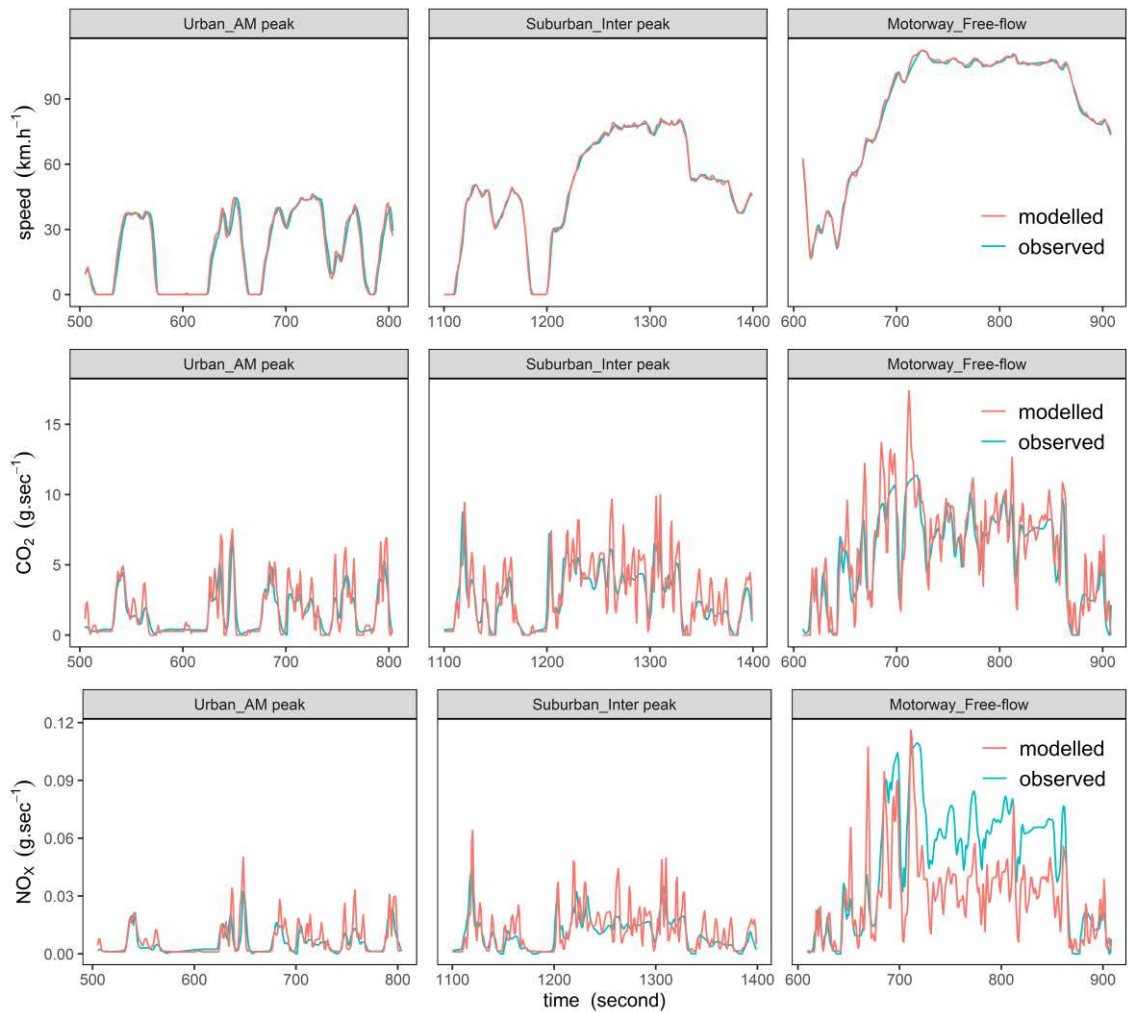


Figure 2 Illustrative time-series plot of different sections of the London Drive Cycle driven by vehicle A (a) speed (top); (b) CO₂ (middle); and (c) NO_x (bottom)

182 In order to study the reason behind the disagreement of observed and modelled
 183 NO_x emissions in free-flow driving conditions, we explored the impact of speed
 184 on both CO₂ and NO_x emissions and the results are illustrated in

$$R^2=0.84$$

(a)

$$R^2=0.67$$

(b)

185 Figure 3. The second-by-second observed CO₂ and NO_x emissions are plotted
 186 against modelled CO₂ and NO_x emissions, and the emission values are grouped

187 by driving mode of that corresponding second. The driving mode definitions
188 proposed by ([Moody and Tate, 2017](#)) are used and expanded:

- 189 • Idle | vehicle speed $< 0.5\text{m/s}^2$ and acceleration in the range $\pm 0.1\text{m/s}^2$;
- 190 • Cruise with normal speed | $0.5\text{m/s}^2 < \text{vehicle speed} < 22\text{m/s}^2$ and
191 acceleration in the range $\pm 0.1\text{m/s}^2$;
- 192 • Cruise with high speed | vehicle speed $> 22\text{m/s}^2$ and acceleration in the range
193 $\pm 0.1\text{m/s}^2$;
- 194 • Acceleration with normal speed | vehicle speed $< 22\text{m/s}^2$ and acceleration $>$
195 0.1m/s^2 ;
- 196 • Acceleration with high speed | vehicle speed $> 22\text{m/s}^2$ and acceleration $>$
197 0.1m/s^2 ;
- 198 • Deceleration | acceleration $< -0.1\text{m/s}^2$.

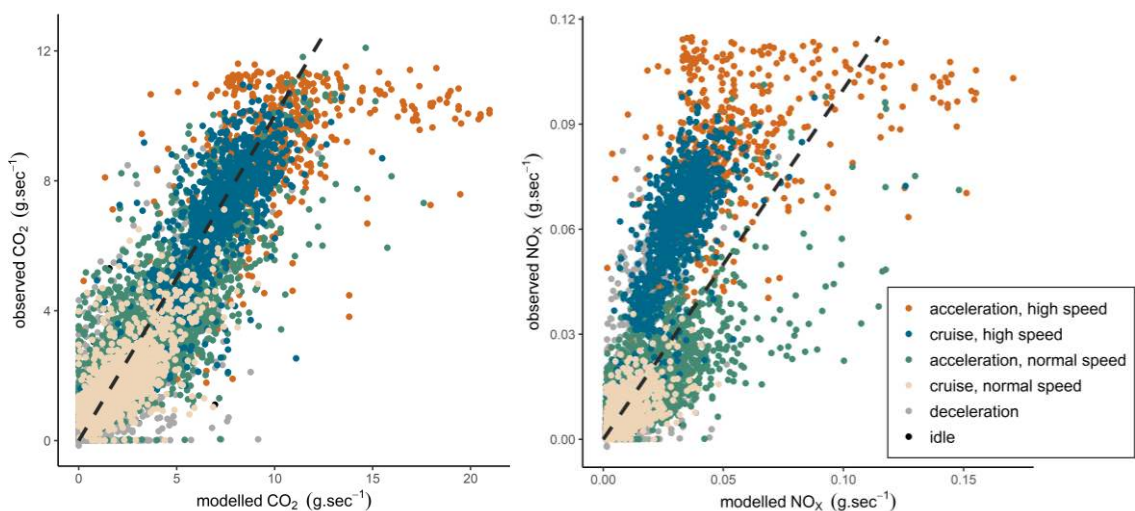
199

$R^2=0.84$
(a)

$R^2=0.67$
(b)

200 Figure 3 illustrate that both CO₂ and NO_x emissions shows strong dependency
201 on driving mode. High speed (top 15% speed range in the LDC) dominates the
202 high emission rates, due to the elevated engine power demands needed to
203 overcome the greater aerodynamic and rolling resistances. The left plot for CO₂
204 emissions shows that the second-by-second observed and modelled CO₂ data is
205 highly consistent and the coefficients of determination (R^2) between observed
206 and modelled CO₂ is 0.84, which demonstrates PHEM's ability to deliver a reliable,
207 transient estimation of real-world CO₂ emissions for different speed ranges. The
208 right plot for NO_x emissions are also in close agreement with the R^2 value of 0.67,
209 and the main deviation between observed and modelled NO_x values is at higher

210 emission rates ($> 0.03\text{g}/\text{sec}$) when a more aggressive driving style (top 15%
211 speed in cruising and accelerating driving mode) is taken. Vehicle A with a EGR
212 after-treatment system has the most effective NO_x control performance during
213 low engine load operation ([Zheng et al., 2004](#)). When the vehicle is driven at high
214 speed (high engine load), it's quite challenging to predict exhaust emissions as
215 after-treatment system performance are more variable. Moreover, PHEM engine
216 power and emission maps are based on an average (normalised) of several
217 vehicles of that category, and there are differences between specific vehicles and
218 fleet averages. In this case, the tested LVC is a heavy diesel van and its engine
219 and emission map may perform slightly worse than the average sized van of its
220 type in PHEM.



$$R^2=0.84$$

(a)

$$R^2=0.67$$

(b)

Figure 3 comparing observed and modelled emission rates for vehicle A by driving mode (a) CO_2 (left); (b) NO_x (right). Black line denotes a 1:1 relationship between the modelled and observed emission rates ($R^2=1$)

221 2.2.3 Loaded van validation

222 To assess PHEM's performance of quantifying the impact of varying load
 223 (weight), vehicle B was tested over the suburban sub-cycle (free-flow and AM
 224 peak) in both un-laden (vehicle B1) and full-laden (vehicle B2) conditions. A
 225 summary of the observed and modelled average CO₂ and NO_x emission rates is
 226 presented in Table 2. It's worth noticing that the observed NO_x emissions were
 227 highest when the un-laden vehicle was driven in AM peak with low speed, stop-
 228 and-go conditions. This is suggested to be due to low engine load (un-laden and
 229 urban driving) operations, resulting in cooler exhaust temperatures and the SCR
 230 system not meeting its operational temperature to achieve effective conversions
 231 and catalytic reductions ([Koebel et al., 2002](#); [Johnson, 2014](#); [Moody and Tate,](#)
 232 [2017](#)). The observed and modelled CO₂ emission rates (g/km) are in close
 233 agreement in both un-laden and full-laden conditions, while the modelled NO_x
 234 emission rates (g/km) are roughly half those from the laboratory tests. Though
 235 PHEM failed to reliably predict the NO_x emission rates of this specific vehicle, it
 236 does capture the trend that the NO_x emissions rates in un-laden conditions are
 237 considerably higher than in full-laden conditions for each sub-cycle.

Table 2 summary of observed and modelled CO₂ and NO_x emission rates from un-laden and full-laden Euro 6 N2 HGV

Pollutant	Time period	Un-laden (g/km)		Full-laden (g/km)	
		Observed	Modelled	Observed	Modelled
CO ₂	Free-flow	291.11	280.66	410.49	400.61
	AM peak	355.63	379.02	530.22	539.10
NO _x	Free-flow	0.27	0.33	0.17	0.11
	AM peak	1.08	0.41	0.46	0.16

238 Figure 4 presents the scatterplot of observed and modelled CO₂ values for un-
 239 laden and full-laden conditions over the chosen test cycle. The frequency of data
 240 points in a hexagonal bin is illustrated on a colour-scale, so both the range in
 241 values and where the core of the data lies are visualised. The scatterplots for CO₂
 242 indicate that PHEM is reliably predicting the dynamics and magnitude of CO₂
 243 emissions under both un-laden and full-laden conditions. The R² between 2930
 244 simulation values and laboratory results are 0.84 and 0.71 for un-laden and full-
 245 laden conditions respectively, demonstrating PHEM's ability to quantifying the
 246 impact of carrying loads on CO₂ emissions.

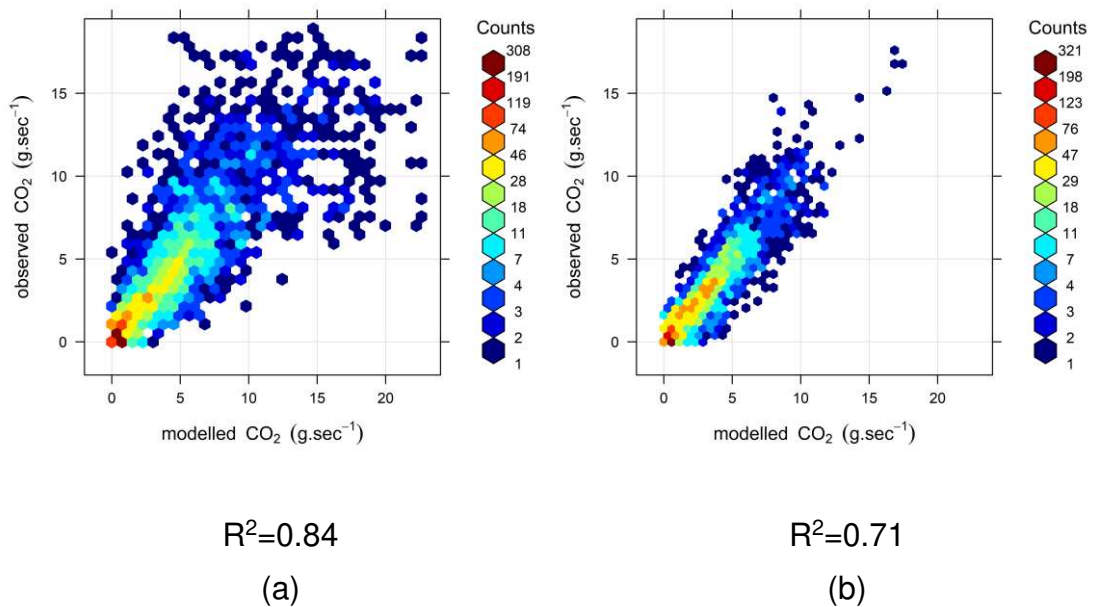


Figure 4 Scatter plots of comparing modelled (PHEM) and observed CO₂ values for suburban sections in free-flow and AM peak (a) 0% payload (left); (b) 100% payload (right)

247 The results in former sections suggest that PHEM accurately estimates the
 248 instantaneous CO₂ emissions from both standard van and loaded small HGV
 249 (and potentially vans). Though PHEM didn't compute the instantaneous NO_x
 250 emission rates very precisely for a specific loaded HGV, it is suggested the test

251 vehicles' engine and emission map deviates from the average vehicle in the fleet
252 that PHEM is attempting to represent. The model does capture the trend and
253 dynamics of the measurements. These validation results suggest PHEM is a
254 suitable modelling tool and capable of simulating the real-world emissions from
255 refrigerated vans including the relative impact of TRUs.

256 **3. Impact of TRUs on vans**

257 **3.1 Additional load of TRUs**

258 The additional load of TRUs on the vehicle engine can be divided into three parts,
259 added weight of the TRUs (insulation material included), increased frontal area
260 of the condenser mounted in front of a van, the refrigeration load (additional
261 electrical load on the engine to power belt-drive compressor). The added weight
262 and frontal area of TRUs can be directly added to vehicle specification in PHEM,
263 and the refrigeration load depends on many external parameters besides TRU's
264 cooling capacity: the ambient temperature and refrigerated compartment
265 temperature; the actual van size and engine type; the load of chilled and frozen
266 food; insulation properties of the isothermal box; door opening times during
267 operating; test cycle and driver's behaviour.

268 To capture the accurate power demand of refrigeration units under real-operating
269 conditions, we calculate the refrigeration load based on [ASHRAE \(2018\)](#) thermal
270 load calculation procedures, which divides the refrigeration load into five parts
271 (represented in Figure 5): (1) transmission load, which is the heat transferred into
272 the refrigerated space through its surface; (2) product load, which is the heat
273 removed from product to keep the refrigerated space in a setting temperature; (3)
274 infiltration air load, which is the heat gain when door opens and air enters into the
275 refrigerated space; (4) precooling load: which is the heat removed from the
276 insulated box and inside air; (5) other load: including heat of internal sources,
277 equipment related load and heat released by human.

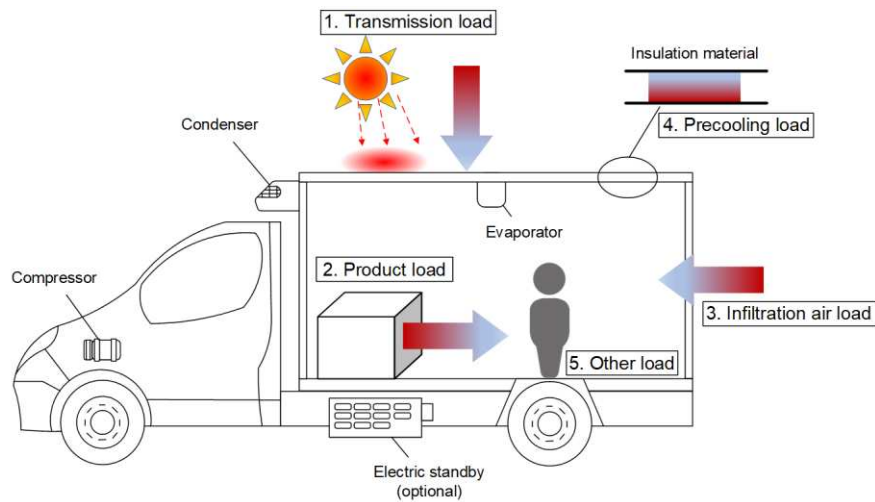


Figure 5 Main sources of heat in refrigerated van

278 This study uses an example to calculate the refrigeration load of the grocery
 279 delivery van and illustrate the temperature and cargo weight impact on the total
 280 refrigerated load of a refrigerated van. We consider a Euro 6a/b class III delivery
 281 van with the following specifications:

- 282 • The internal dimensions of the insulated box are 3.4m long, 1.0m wide and
 283 1.8m high (see Figure 6-a); the box is made up with four compartments:
 284 one ambient compartment, one frozen compartment with the setting
 285 temperature of -18°C , two chilled compartments with the setting
 286 temperature of 2°C ; the dimensions for each compartment is stated in
 287 Figure 6-b.
- 288 • The roof, the walls, the doors and the floor are made up of 60mm
 289 polyurethane foam ([Ashida, 2006](#)), with thermal conductivity
 290 $0.0228\text{W}/(\text{m}\cdot\text{K})$ ([Tassou et al., 2009](#)). Between each compartment an
 291 insulated bulkhead is installed, and the bulkhead is also made up of 60mm
 292 polyurethane foam.

- 293 • The total delivery time is assumed to be 8 hours per day, delivering to 4
294 customers per hour (figures established on interview). For every customer,
295 the driver will keep the frozen compartment door and one of the chilled
296 compartments door open for 1 minute.

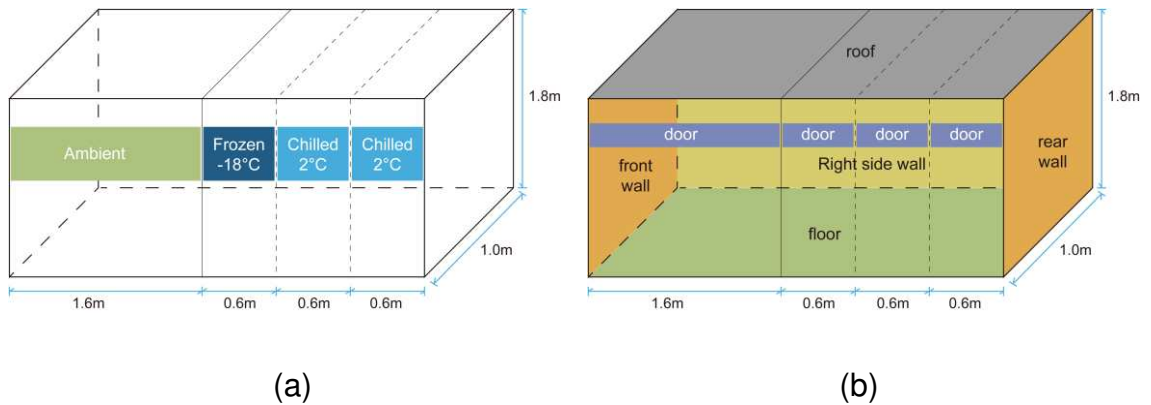


Figure 6 (a) internal dimensions and setting temperature of each compartments (left); (b) schematic diagram of the insulated box of a delivery van (right)

297 Only transmission load and infiltration load are considered for simplification here.
298 The complete calculation procedure is documented in the supplementary
299 material. In order to evaluate the impact of ambient temperature on total
300 refrigeration load, this paper uses three illustrative temperature settings, from
301 40°C in the summer, 20°C in spring/autumn to 0°C in the winter. When comparing
302 the total refrigeration load in different temperature (see Table 3), considerable
303 reduction is found as the temperature decreases, which demonstrate the
304 significant effect of ambient temperature on refrigeration load.

Table 3 total refrigeration load in different temperature

Temperature, °C	Transmission load, kW	Infiltration load, kW	Total refrigeration load, kW
40	0.31	2.63	2.93
20	0.18	1.75	1.93
0	0.06	0.73	0.78

305 **3.2 Fuel consumption and exhaust emissions from refrigerated vans**

306 Impact of TRUs on a Euro 6a/b class III van with average loading of 375kg
307 (default setting in PHEM) was assessed by PHEM over the LDC. When
308 considering the additional load of TRUs, an added 135kg TRU weight, 0.23 m²
309 increased frontal area and 1.93 kW refrigeration load at an ambient temperature
310 of 20°C were added to vehicle specifications in PHEM over the full 140km LDC.
311 These were contrasted with emissions from the same base Euro 6a/b class III
312 standard van with 375kg loading following the same driving trajectory and
313 conditions. In both refrigerated van and standard van simulations, the SCR
314 module is activated, as Euro 6a/b class III van are commonly equipped with SCR
315 after-treatment system to mitigate NO_x emissions.

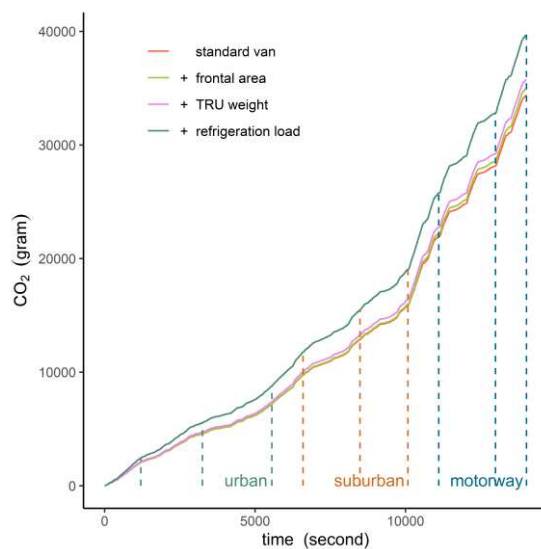
316 Simulation results shows that average CO₂ emission for a refrigerated van is 282
317 g/km, 15% higher than standard van, while average NO_x emission factor for a
318 refrigerated van is 0.43 g/km, 18% higher than standard van. The real-world CO₂
319 emissions from refrigerated vans is nearly 2 times the government's target (147
320 g/km) and NO_x emissions more than 3 times the Euro 6ab limit (0.125 g/km).

321 The increased frontal area, added TRU weight and additional refrigeration load
322 were added respectively in PHEM to assess their impact on CO₂ and NO_x
323 emissions performance.

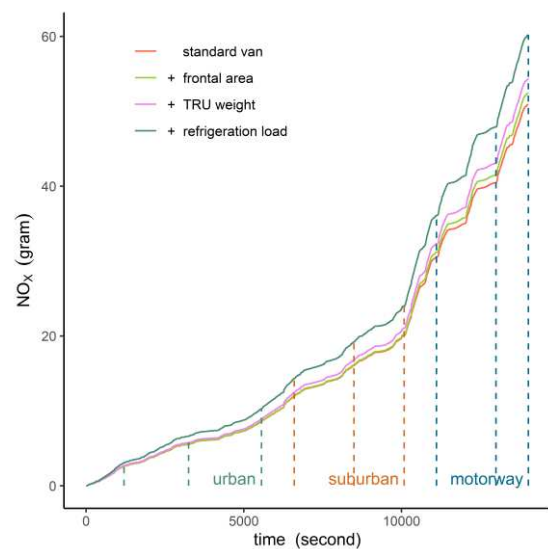
(a)

(b)

324 Figure 7 illustrates these additional loads over the whole LDC at an ambient
325 temperature of 20°C, and slope in each sub-cycle represents the average
326 emission rate per second (g/sec) for different driving conditions. It's clear that the
327 refrigeration load contributes to the largest share of additional CO₂ and NO_x
328 emissions.



(a)



(b)

Figure 7 cumulative plot of (a) CO₂ emissions (left) and (b) NO_x emissions (right) at an ambient temperature of 20°C (different parts of TRU load)

329 The refrigeration loads in 3 ambient temperature scenarios specified in Table 3
330 were added to PHEM as auxiliary electrical engine loads, with the standard TRU
331 increased frontal area and additional weight also applied. Table 4 summarizes
332 the impact of ambient temperature on CO₂ and NO_x emissions from refrigerated
333 vans, as well as the relative contribution of these three additional loads. A high

334 ambient temperature of 40°C is found to impose a significant additional auxiliary
 335 power load for cooling, and associated increases in fuel consumption and NO_x
 336 emissions. In all ambient temperature scenarios, the refrigeration load is found to
 337 account for the majority of the additional emissions associated with equipping the
 338 vehicle with a TRU. The results demonstrate the need to minimise refrigeration
 339 load through storage compartment and door opening management/strategies,
 340 especially when ambient temperature is high, for the heat gain through the
 341 insulation box and from air infiltration when door is open and closed is
 342 considerable.

343 Moreover, the increase in emissions may be partly offset by a “low temperature
 344 NO_x emission penalty” found in diesel vehicles ([Grange et al., 2019](#)), where
 345 ambient temperature has an impact on diesel vehicle’s post-combustion control
 346 technology and high temperature resulting in lower NO_x emissions. Vehicles
 347 equipped with LNTs (lean NO_x traps) shows more temperature dependency than
 348 vehicles with SCRs.

Table 4 Impact on the CO₂ and NO_x emissions by various ambient temperature

Pollutant	Ambient temperature, °C	Emission rates, g/km	Share of different parts in additional emissions		
			Frontal area	TRU weight	Refrigeration load
CO ₂	40	297	8%	10%	82%
	20	282	11%	14%	74%
	0	265	21%	26%	53%
NO _x	40	0.45	12%	16%	72%
	20	0.43	16%	21%	62%

0	0.40	27%	35%	38%
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349 In Table 5 two sub-cycles (free-flow and AM peak time period in suburban areas)
350 were chosen to contrast refrigerated van's emission performance with different
351 cargo loading under different driving conditions. Loading factors from un-laden
352 (135kg TRU weight counted), average-laden (375kg cargo plus 135kg TRU
353 weight) to full-laden (1265kg cargo plus 135kg TRU weight) were added in
354 PHEM. Unlike the emission test results in the validation process in Table 2, NO_x
355 emissions are higher in full-laden conditions than in un-laden conditions, which
356 might be due to the fact that refrigerated vans already have additional TRU weight
357 even in un-laden conditions, providing enough exhaust emission temperature for
358 SCR to work efficiently. Both CO₂ and NO_x emissions are higher when vehicles
359 were driven in AM peak traffic conditions. Further research, perhaps including
360 chassis dynamometer test or portable emission measurement is suggested to be
361 needed, to study the cause and impact of loading on refrigerated vans.

Table 5 the influence of grocery weight and driving condition on emission rates for a Euro 6 class III refrigerated van (20°C ambient temperature)

Pollutant	Time period	Un-laden (g/km)	Average-laden (g/km)	Full-laden (g/km)
CO ₂	Free-flow	209	223	255
	AM peak	264	280	322
NO _x	Free-flow	0.27	0.30	0.39
	AM peak	0.33	0.37	0.49

362 Simulation results over the realistic London Drive Cycle suggest significant
363 differences of CO₂ and NO_x emissions between standard vans and refrigerated
364 vans. The influence of higher ambient temperatures, heavier loading factor and
365 stop-start driving condition on emissions are is also worth attention. Findings
366 confirm the need to take into account the impact of additional engine load when
367 predicting refrigerated van emissions.

368 Aside from higher emission factors for refrigerated vans, demand for grocery
369 home deliveries has surged since the outbreak of COVID-19, and the rise is
370 expected to be sustained as the pandemic has brought new customer to online
371 grocery and many would retain the habit. Mintel⁶ estimates the market to be worth
372 £17.9 billion by 2024, growing by 41% over the five year period, resulting in a
373 significant growth and associated environmental impact of refrigerated vans.

⁶ <https://www.mintel.com/press-centre/retail-press-centre/mintel-forecasts-online-grocery-sales-will-grow-an-estimated-33-during-2020>

374 4. Summary and conclusions

375 Analysis conducted in this study aims to understand the contribution of TRUs to
376 CO₂ and NO_x emissions from vans. By simulating the CO₂ and NO_x emissions of
377 vehicles measured on the chassis dynamometer, PHEM has been proven to be
378 a model capable of estimating instantaneous emissions for vehicles carrying
379 loads. Real-world CO₂ and NO_x emission factors for refrigerated vans have been
380 developed using PHEM, and the analysis highlights the following findings:

- 381 • Vans with TRUs generate ≈15% more CO₂ emissions and ≈18% more NO_x
382 emissions than standard vans.
- 383 • The impact of TRU weight, frontal area and electrical load on the engine
384 by the TRU on emissions were independently assessed, illustrating that
385 the refrigeration load is the most significant cause of excess emissions,
386 contributing increase of 74% and 62% to CO₂ and NO_x emissions
387 respectively.
- 388 • The burden of additional emissions of a TRU van becomes more
389 significant in higher ambient temperature as the refrigeration load
390 increases. Stop-start driving conditions and heavier cargo loading are also
391 shown to elevate emissions.

392 Analysing the difference between standard van and refrigerated van by PHEM is
393 important in three ways. Firstly, simulation results confirm the need to take into
394 account the effect of additional load when predicting refrigerated van emissions
395 and fuel consumption. Secondly, findings on the impact of temperature, grocery
396 loading and driving conditions on refrigerated van emissions can be used to
397 improve fuel-saving and eco-friendly strategies in grocery delivery. Moreover,
398 PHEM is capable of evaluating the impact of real-world factors on emissions.

399 Local policy makers can adjust the vehicle parameters so that they are specific
400 to their own applications and situations.

401 Van traffic is forecast to continue growing significantly and make up between 14%
402 and 21% of traffic mileage by 2050 ([DfT, 2018a](#)), in the meanwhile results in this
403 study suggests that real-world emission factors of standard vans are higher than
404 official statistics. It is both timely and significant to accurately assess the real-
405 world van emissions as city authorities consider whether to include restrictions
406 on vans in policies such as Low Emission and Clean Air Zones ([Defra, 2018](#); [DfT,](#)
407 [2020](#)).

408 Recommendations for further research include laboratory (chassis
409 dynamometer) test for refrigerated vans under different scenarios, to study the
410 impact of changing ambient temperature, door opening times or weight of cargo.
411 A special test (drive) cycle could also be designed to assess the influence of
412 driving conditions and refrigeration unit designs/operation. Besides, further
413 research could also focus on the environmental impact from all the other kinds of
414 vans with extra loading, like ambulances which are always high powered and
415 heavy loaded, and to include different measurement or estimation methods like
416 laboratory (chassis dynamometer) testing, on-road (PEMS), remote sensing and
417 simulations.

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